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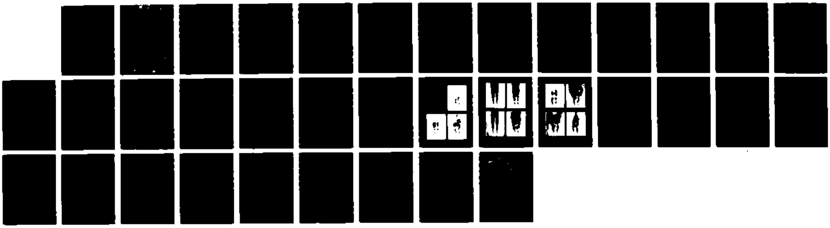

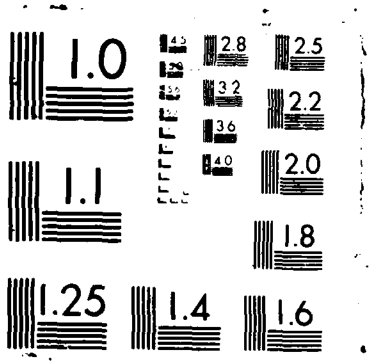
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This report outlines a coordinated new set of research programs on flow control. The work is being carried out by a team of experts in fluid mechanics and automatic control. Jets, turbulent boundary layers near separation, and delta wing flows form the basis for these studies, aimed primarily at developing fundamentals needed for active control of flows of technical interest.

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1987 Annual Report

to the

Air Force Office of Scientific Research

on

Research in Flow Control

performed under contract F49620-86-K-0020

Report Edited by

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Program Coordinator

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and
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October 30, 1987

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1. Overall Program Objectives

This program is a coordinated set of research activities in *flow control*. The broad program objectives are to advance the basic knowledge needed for implementation of new techniques for control flows of interest to the Air Force, and to carry out initial demonstrations of those techniques. The work is being carried out by teams of faculty and Ph.D. student Research Assistants in the Departments of Aeronautics/Astronautics and Mechanical Engineering at Stanford. Faculty expertise in fluid mechanics, automatic control, turbulence, advanced instrumentation, and aeronautics is involved throughout the program. The program also serves as the basis for training several Ph.D. students in the emerging field of flow control.

The research program currently has three primary program elements:

1. Control of jet flows;
2. Control of unsteady turbulent boundary layers;
3. Control of vortical flows over delta wings.

The objectives, progress, and future plans of each of these three program elements are described below.

This is the first annual report of this project. For most of the program elements this was an initiation year, devoted to the build-up of laboratory capability, experiment design, and preliminary experiments. For some program segments the new work is an extension of work already started, and therefore with more new results to report. Overall, quite a bit of progress can be seen in the reports that follow.

2. Control of jet flows

a) Background

This program is an outgrowth of the initial research on bifurcating and blooming jets carried out by Prof. W. C. Reynolds and his students under a prior AFOSR contract. Prof. J. David Powell, a controls expert, has joined the team to provide expertise needed for ongoing feedback control experiments.

In the initial work it was found that, by properly combining axial and azimuthal forcing, round jets at Reynolds numbers of the order of 4000-10,000 could be made to bifurcate into two separate jets, or to "bloom" into a shower of vortex rings. The blooming jet spreads at an angle of approximately 80 degrees, much more rapidly than a normal jet, and hence its momentum is mixed with the surrounding fluid much more rapidly than in a normal jet. Scalar mixing is also enhanced. This initial work was done in water, using orbital motion of the jet nozzle to provide the azimuthal excitation.

Control over these flows is achieved by controlling the discrete vortex structure in the near field of the jet. The shear layer flowing from the nozzle lip tends to roll up into concentric vortex rings, and the phasing of these is controllable by the axial excitation. If these rings can be made eccentric, as for example by slight orbital motion of the nozzle, and the ring spacing is in a particular range, they will tilt one another and fly off in different directions, causing bifurcation (two rings per orbit), trifurcation (three rings per orbit), or blooming (non-integer rings per orbit). The ratio of the axial to the orbital frequency determines which flow pattern will appear. The flow regime is also sensitive to the excitation amplitude, which need not be very large. Subsequent work with a simple air apparatus showed that acoustic excitations could be used with gas flows, at Reynolds numbers up to 20,000.

At these low Reynolds numbers the initial shear layer is laminar and the natural spacing of the ring vortices in the shear layer is close to the spacing at which the eccentric rings will tilt one another without becoming entangled, a condition necessary for bifurcation or blooming. But at high Reynolds numbers the natural initial ring spacing is much closer, and the axial excitation must be sufficient to cause a "collective interaction" that will amalgamate closely-spaced rings into rings spaced in the right range for effective tilting. At even higher Reynolds numbers the ring vortices become turbulent before the tilting process, making them difficult to control.

b) Objectives and basic approach

The objectives of the current program are:

1) to explore the mechanisms by which jet flows at higher Reynolds numbers and Mach numbers can be controlled by dual-mode excitation;

2) to extend the Reynolds number and Mach Number range over which control can be effected;

3) to use these flows as a basis for developing the basic engineering science of flow control.

Research on automatic control is currently being conducted in the low-speed air apparatus, where the processes are well understood. Experiments aimed at extending the range of control to more difficult conditions are being carried out in a new air facility. The original water facility is being used to explore new concepts in which the flow itself provides the required oscillatory forcing. Numerical simulations using vortex dynamics were carried out under the previous AFOSR contract and will be extended when helpful in the current research.

c) Progress and plans

A new apparatus capable of achieving Reynolds numbers in excess of 150,000 and Mach numbers of at least 0.3 has been constructed. This device uses loudspeaker excitation, with a single speaker in the plenum for axial excitation and four speakers with waveguides around the nozzle exit for azimuthal excitation. The system is installed in a newly-constructed laboratory where the beam from a copper-vapor laser is available for flow visualization experiments.

With this apparatus we have shown that dual-mode acoustic excitation can be used to control the jet at least up to Reynolds numbers of 100,000 and Mach numbers of 0.22. This represents a significant advance in dual-mode jet control, and was reported recently at the Sixth Symposium on Turbulent Shear Flows; for details see Appendix A.

We plan to obtain quantitative data on the detailed flow structure and would prefer to use hot wire anemometry. Currently we are exploring design options for flying hot wire systems, and we expect to assemble this system and begin to acquire data later this year.

While awaiting the flying hot wire system, we are now characterizing the required excitation amplitudes using available hot-wire instrumentation. Although the required excitation amplitudes are small with respect to the flow power, as we increase the flow speed the absolute excitation power is at the edge of what can be achieved with loudspeakers, so an alternative approach will be needed if we are to push to higher speeds.

We have begun a quest for new ways to use the flow itself to generate the required excitations, so that as the flow power is increased the ratio of excitation power to flow power will remain constant. This initial work is being carried out in the original water facility because we prefer a method that depends on flow mechanisms rather than acoustics, and the water tests eliminate acoustics. The basic idea is to use the signature of the ring vortices passing stationary points in the flow as the source of a pressure disturbance, which will be fed back to the jet nozzle lip at the appropriate phase for flow control. We hope to achieve the dual-mode excitation by using two separate vortex signature reflectors. If this approach is successful in water it should work in air and we will try it on the air facility.

The original air unit, which utilizes a single loudspeaker in the nozzle plenum to provide the axial forcing and four speakers around the nozzle exit to provide the azimuthal excitation, is being used as the basis for the control research. The bifurcating/blooming jets represent a complex flow that can be dramatically modified by the right kind of excitation, for which the basic flow processes are now well understood. Hence these flows provide an excellent point for exploring fundamental issues in flow control, such as sensor placement and feedback control. The purpose of this phase of the program is to gain some basic understanding of the problems that will be encountered when one attempts to control complex flows, and to introduce our faculty experts in automatic controls to the general area of flow control.

The initial step was to construct a partially-automated system. It required manual setting of phase shifts crucial for control of the flow, and pointed up problems in the basic sensing. For example, the plenum pressure sensor used to determine instantaneous flow rate was exposed to the acoustic resonances in the chamber, which had to be filtered out for success.

The next step was to modify the system to make it completely open-loop controllable using a minicomputer as a control element, and this has been completed. In addition, a shroud has been added to the jet, so that in essence it becomes a jet ejector (thrust augmentor). We have shown that blooming can be effected in the shroud, which hints at the possibilities of improved performance in thrust augmentors by this method of flow control. The secondary flow entrainment can be measured fairly easily with the shroud in place, and hence this system will provide an interesting basis for study of optimal closed-loop control, in which the excitation frequencies are adjusted for maximum performance. For more details see Appendix B.

d) Participants

Faculty co-principal investigators:
  Prof. W. C. Reynolds (fluid mechanics)
  Prof. J. David Powell (controls)

Graduate Research Assistants:
  David Parekh (jet structure) Ph.D. expected 1988
  Philipe Juvet (jet structure) Ph.D. expected 1990-90
  Robert Koch (jet control) Ph.D. expected 1989
  Michael Sasges (jet control) (no cost) M.S. June 1988

There is frequent exchange of information, ideas, and equipment among the participants and between them and others in the extensive fluid dynamics and automatic controls communities at Stanford.

3. Control of unsteady turbulent boundary layers

a) Background

Unsteady turbulent boundary layers arise on flight vehicles during maneuvers, and in turbomachinery and other situations of interest to the Air Force. The ability to control these boundary layers, either to prevent separation or to cause the separation to occur in some desired way, would offer important technological advantage. For example, the control of vortical flow over a delta wing, discussed in section 4 below, is an example of flow control through control of the boundary layer separation point (in that case by tangential blowing).

This program is concentrating on boundary layer control by active vortex generators. The work deals both with the unsteady vortical fields generated by dynamic vortex generators and with the response of the boundary layers to these unsteady control vortices.

The work on the flow field generated by the control devices is a follow-on to work on steady longitudinal vortices carried out under Professor J. K. Eaton. It is motivated by the need for a detailed understanding of the flow structure and vortex propagation in order to make optimal use of actuated vortex generators for flow control.

The work on the response of unsteady turbulent boundary layers to these control vortices follows work on unsteady boundary layers directed by Professor W. C. Reynolds. This work concentrates on the vorticity transport in the boundary layer and on the control of vorticity transport by unsteady longitudinal vortices. The work includes a sub-project to develop a new method for direct optical measurement of the vorticity field, being carried out under the direction of Professor Hesselink.

b) Objectives

The objectives of this work are as follows:

1) to develop basic knowledge of the flow field generated by unsteady actuation of delta-type longitudinal vortex generators in turbulent boundary layers under zero and adverse pressure gradient;

2) to develop basic knowledge of the response of turbulent boundary layers under unsteady adverse pressure gradients to the actuation of longitudinal control vortices;

3) to develop new methods for direct optical measurement of the vorticity in water flows, for use in this research.

These objectives form the basis for three segments of this program, reported below.

c) Progress and plans

Vortex actuator flow field

This segment of the program is under the direction of Professors J. K. Eaton and J. P. Johnston. Because of Eaton's sabbatical in 1987, only start-up work was planned for the first year, with significant acceleration built into the program plan and budget for the second year.

The first phase the study has focused on a half-delta vortex generator and is being conducted in a low-speed air flow facility. A printed circuit motor actuator which allows actuation rates up to 9000 degrees/sec was constructed, and measurements have been completed for one case: a 2 cm high delta wing pitched from 0 to 18 degrees in approximately 20 msec. Phase-conditioned data were acquired with an x-array hot wire probe which can resolve both the temporal and spatial structure of the evolving vortex. Data including all three velocity components were acquired in planes perpendicular to the flow direction with 56 measurement points in each plane. Interpretation of the large amount of resulting data is difficult, and has been aided considerably by use of an IRIS Graphics Workstation in the Center for Turbulence Research at Stanford, which was recently upgraded with the help of an AFOSR equipment grant.

The second phase of the study has been the construction of a new adverse pressure gradient wind tunnel adjacent to our existing zero pressure gradient longitudinal vortex tunnel. The new tunnel has a flat test wall with removable sections for the installation of vortex generator arrays. New methods for impulsive generation of longitudinal vortices will be examined in the first work in this tunnel. The pressure gradient is controlled by contour of the opposite wall. A new Masscomp MC5400 computer system has been ordered which will provide high-speed data acquisition and control capability for both the new and existing vortex flow tunnel.

The next step in this program is to use both vortex wind tunnels to examine temporal and spatial development of vortices behind a variety of actuated vortex generators. Key features to be identified for each generator are the initial structure, the convection speed of that structure, and the time lag between actuation and the achievement of steady vortex flow. The process of acquiring and processing the data is being fully automated so we can examine several different classes of vortex actuators.

This segment of the research will be merged with the AFOSR sponsored program on active control directed by J.K. Eaton and D.J. Koga. The use of vortex generators to modulate vorticity outflow from an unsteady separation bubble will be examined. Time lag information acquired in the present phase of research will be critical in establishing phase relationships for an active control loop. Out first simple active control loop will use one of the vortex actuation techniques and a thermal tuft flow direction sensor detecting incipient separation in an unsteady adverse pressure gradient.

Unsteady boundary layer control

This work is being conducted under the direction of Prof. Reynolds. The experiments on boundary layers under unsteady free-stream conditions are being performed in a water tunnel originally built for an ARO-supported study of unsteady boundary layers. This tunnel has recently been extensively rebuilt to provide improved optical access for diagnostics and great flexibility in the unsteady free-stream flow. The rebuild has been part of a Navy-supported program of research on unsteady three-dimensional laminar boundary layer separation, and the new system is designed to deal with both laminar and turbulent boundary layers.

The test surface is provided by one flat wall of the channel, with a fresh leading edge at the entrance to the test section. Sidewall boundary layers are removed periodically through suction slots. The flow through the channel can be removed through the wall opposite the test section, creating an adverse pressure gradient along the test surface. By draining uniformly across the span a two-dimensional free-stream flow is created, but by draining non-uniformly a three-dimensional free-stream flow can be imposed on the test boundary layer. Alternatively, the exit flow may be confined to the end of the test section, providing a zero pressure gradient free-stream flow along the test surface.

The draining, and hence the imposed free-stream flow, can be steady or unsteady. Printed-circuit motors are used to control nine drain valves of special design through a custom computer interface. The valves may be placed at a wide variety of locations along the test section, allowing for a very wide variety of possible unsteady free-stream conditions of two or three dimensional character. The computer control allows any waveform to be used; sinusoids, square waves, and triangular waves are pre-programmed. The valves can be controlled to produce a steady flow in the upstream portion of the test section and an unsteady flow downstream, thereby eliminating variations in leading edge vorticity. Or, the entire flow can be oscillated so that the added influence of leading edge vorticity fluctuation can be investigated.

Special precautions have been taken to assure reliable, repeatable experiments. A refrigeration system operating under very tight automatic control maintains the water temperature within a fraction of a degree at all times. Air is removed from the water by a continuously operating system, to prevent microbubbles from contaminating the LDA measurements. The inlet flow is carefully conditioned by honeycombs and screens, which produce a free-stream turbulence level measured to be no more than 0.6%. Long, clean runs of laminar boundary layers can be formed on the test surface, suggesting that the free-stream turbulence is lower than inferred from noise-prone LDA measurements.

A two-component LDA mounted on a special computer-controlled mobile breadboard is used for velocity surveys, which are automated and may extend over many hours without intervention. Another LDA can be used for monitoring the free-stream conditions or for obtaining a third velocity component. A wall-fan-fringe optical skin friction detector, developed in this facility, is also available.

During the past year we completed the rebuild of this facility and put it into operation. As with any new facility, some debugging was required, and it is important to begin by requalifying the basic flow. This required careful adjustment of the leading edge flow around the test surface, the side-wall boundary layer suction flows, and the bleed flows used to set zero pressure gradient along the test section. Since the LDA instrumentation had been disassembled during the rebuild, it had to be reassembled and the new research students had to gain experience with its use. This is now behind us, and we are beginning to conduct the first experiments in the facility. A preliminary report on the unsteady separated laminar flow work (ONR support) was made at the AFOSR workshop on Unsteady Separated Flow in Colorado Springs, July 1987.

Work in this facility under the present AFOSR contract will deal with control of unsteady turbulent boundary layers using longitudinal vortices produced by actuated vortex generators. The turbulent flow region of the test surface is built to accommodate an array of actuated vortex generators, and a first array is now being fabricated.

The first step in the turbulence experiments will be to document the basic unsteady turbulent boundary layer flow. An unsteady condition sufficient to produce periodic separation will be selected, and the boundary layer will be documented, first without the generator vortex array and then with the array in place at zero angle of attack. Next, the vortex generators will be pitched on at a selected point in the cycle of the unsteady flow, and we will try to delay or eliminate the separation. If this control is effective, as we believe it will be, then we will attempt to close the loop and use a separation sensor to activate the vortex generators.

The principal student researcher on this work is Air Force Major William Humphreys, who will return to the Air Force Academy faculty upon completion of his Ph.D. degree.

Direct vorticity measurement

This work is being conducted under the direction of Prof. Hesselink. Vorticity and strain rate are crucial features of turbulent flows that are difficult to measure. The normal approach is to make velocity measurements at nearby points, then the differences in these data to get the velocity gradients. Accuracy in the velocity difference requires extremely accurate measurement of the velocities, and accuracy in the gradients requires accurate knowledge of the separation distance between the two measurement points. The technique being explored here provides a direct measurement of the velocity gradients, and hence should be less prone to these difficulties.

The idea is to record a volume phase hologram in the fluid and then to read out the deformation of the resulting grid by optical methods. The fluid must contain a photochromic substance that can be sensitized to create the hologram. The deformation must be inferred by the diffraction pattern of a read-out beam passed through the hologram. The elements of this idea are not new and are well known in Prof. Hesselink's laboratory. The challenge is to put them together in a way that becomes useful for flow experiments, and eventually to bring this technology into the unsteady water flow facility.

The initial work is being conducted in Prof. Hesselink's optics laboratory. A survey of the literature revealed promising photochromic dyes, and four were selected for detailed evaluation. All four types were investigated in some detail, but only benzopyran dyes proved to be suitable.

The green (510 nm) line of a 20-watt pulsed copper-vapor laser is suitable for bleaching these dyes. The coherence length of these lasers has been found to be about 2.5 cm, sufficient for forming the hologram. The use of a benzopyran dye to write and read out holograms was successfully demonstrated during the past year.

Commercial copper vapor lasers offers a high repetition rate (6 kHz), giving hope that a semi-continuous measurement scheme can be developed. However, improvements in these devices are necessary in order to use them for holograms, and some progress on this has been made as part of the present effort. As yet unresolved problems include laser beam divergence, which is rather large when using stable resonator optics; the divergence can be reduced significantly by switching to unstable optics, but the resulting beam contains a doughnut hole that hampers optical manipulation. Air currents caused by beam heating also cause problems. Continued effort at improving these systems, in collaboration with the manufacturer, is anticipated.

A major achievement of the first year has been a careful analysis of the modeling of moving holograms and their readout. Two papers on this subject have been submitted for publication in the Journal of the Optical Society of America. These papers and other work as yet not submitted provide analytical expressions relating the angular moments of the diffracted light in the readout beam to the velocity distribution within the measuring volume. They form the basis for this new type of direct measurement.

The analysis consists of three main ingredients: hologram recording, deformation and diffusion of the hologram, and the optical readout. The convection and diffusion problem is solved in the Fourier domain for simple flow cases, The diffraction computation uses the results of the flow problem in terms of the Fourier space distribution and makes a plane wave decomposition of the incoming light. This information was crucial in the design of the optical architecture being employed in this research.

A dedicated data acquisition system has been acquired and installed for purpose of recording and analyzing the time evolution of the diffracted light from the readout beam passing through the convected hologram. A position detector for the diffracted beam has been constructed using an extended area PIN photodiode, and is fully operational.

A small, portable, closed-loop water flow channel suitable for the initial flow experiments has been borrowed from Prof. Reynolds laboratory. This system provides a steady, known plane Poiseuille flow, which will serve as the initial test flow for the new technique. Our goal is to bring this technology to the point where it can be used in the full-scale water flow channel in two to three years.

d) Participants

Faculty co-principal investigators:
Prof. J. K. Eaton (vortex actuator/flow measurements)
Prof. J. P. Johnston (boundary layer separation)
Prof. W. C. Reynolds (unsteady boundary layers)
Prof. L. Hesselink (optics)

Research Associates:
Dennis Koga (fluid mechanics, electronics, flow control)

Graduate Research Assistants:
William Humphreys (unsteady b.l. control) Ph.D. 1988
Andrew Carlson (electronics, controls) Ph.D. 1988
Keller Strother (vortex flow fields) (no cost) M.S. 1988
Howard Littell (vortex actuators) (no cost) M.S. 1988
Juan Agui (optical measurement of vorticity) Ph.D. 1988

Visiting Scientist:
Dr. M. Nishii, Kyushu Institute of Technology (no cost)
(separation control with vortex generators)

4. Control of vortical flow over a delta wing

a) Background

In a study at Stanford under NASA/Ames support, it was discovered that the vortical flow over a delta wing can be controlled by tangential blowing along the (blunt) leading edge. The blowing strength controls the separation point and hence the rate at which vorticity is shed into the free stream, and this controls the external flow structure. With blowing, high lift can be attained at much greater angles of attack than without blowing. And, unequal blowing on the two sides can be used to establish asymmetric flow fields, hence a roll moment. Blowing also seems to stabilize the external vortical flow field, probably by stabilizing the location of the boundary layer separation. This program seeks basic understanding of the flow phenomena involved and exploration of the possible use of this technique for control of the steady and unsteady flow fields over a delta wing.

b) Objectives

The objectives of this program are as follows:

1. to develop a basic understanding of the process by which boundary layer separation regulates the unsteady vortical flow over a delta wing;

2. to implement an advanced quantitative flow visualization system for study of this flow;

3. to examine special problems of feedback control of complex vortical flow fields over lifting surfaces, advance the theoretical models for control model development, and implement active control of the flow for a wind tunnel model.

c) Progress and plans

At the start of this AFOSR project, the basic concept had been demonstrated on a steady-flow half-delta model mounted on the wall of a small wind tunnel. This model was instrumented for steady pressure measurements, and was used to demonstrate the dramatic increase in lift performance that accompanies leading edge tangential blowing.

The new work was designed to look at unsteady flow, and active flow control. This required major revamping of the wind tunnel facility and a new test model.

The low-speed wind tunnel in the Aeronautics/Astronautics Department was repaired, upgraded, and recalibrated for speeds of 5-20 m/s. The laboratory was rearranged to enable the use of a copper-vapor laser for the flow visualization studies.A new data acquisition system based on an IBM PC-AT was put into service. This provides sampling at up to 130 kHz on sixteen single-ended A/D channels, with 2 channels of D/A and 16 channels of digital I/O. Special display software has been written, and this system is now operational.

An unsteady blowing system capable of full alteration of the blowing in 3-5 ms has been constructed and placed in operation. Flow visualization experiments mode with this unsteady blowing system using the old wing model were presented at the AFOSR workshop on unsteady separated flow in July, 1987 (see appendix C). They show rapid and dramatic response of the external flow field to adjustments in the blowing rate. A video tape of these results has been provided to AFOSR and is available from Prof. Roberts.

A new wind tunnel model was designed and fabricated. This model is suitable for transient blowing experiments and has other useful features not present in the original model. his model has the following features:

1) constant radius leading edge with variable slot height capability;
2) nearly constant thickness with a sharp trailing edge;
3) unsteady surface pressure sensors (upper surface);
4) real-time strain gage balance mounting for direct measurement of normal force, pitching moment, rolling moment and drag;
5) trailing edge flaps.

It is anticipated that in future work the trailing edge flaps would be oscillated to provide an unsteady aerodynamic input that could stimulate control by the leading edge blowing.

Open-loop flow control by fast response blowing has already been demonstrated. Future work will concentrate on the gathering of basic data on the flow field needed to decide how to sense the flow in order to provide information for feed-back control of the blowing, and then on implementation of blowing control. This work is being conducted under the direction of Professor Roberts and Dr. Norman Wood.

An advanced optical system is being assembled under the direction of Professor Hesselink. This system will use scanning sheet illumination from a copper vapor laser. The equipment for this has been obtained and is now being assembled. Various options for scattering particles or droplets are being explored. It is hoped that this advanced system will be ready for operational use in the wind tunnel later this year.

Under Professor Kroo, theoretical work has been initiated on a mathematical model for the unsteady aerodynamics over a delta wing. This model is needed both as an aid to understanding of the flow and as an element in any future control system.

A non-linear model has been developed, and the attached flow case tested, with results comparing well to both experiments and previous analyses.. The leading edge separation and the resulting vortical flow above the wing are now being added to this inviscid model. The next step will be to introduce an empirical relationship relating the separation point movement to the blowing velocity. It is expected that all of this will come together to provide a working model of the external flow within the next year.

This model will be tested and adjusted by reference to the wind tunnel data. Its first use will be to guide the placement of surface sensors used for the feedback control, and ultimately it may become a dynamic part of the control system itself.

d) Participants

Faculty co-principal investigators:
- Prof. L. Roberts (aerodynamics; overall coordination)
- Prof. I. Kroo (aerodynamic modeling and control)
- Prof. L. Hesselink (optics)

Research Associate:
- Norman J. Wood (fluid mechanics, measurements)

Graduate Research Assistants:
- K.T. Lee (wind tunnel experiments) Ph.D. 1990
- Minami Yoda (optical systems) Ph.D. 1990
- Zeev Mittelman (aerodynamics model) Ph.D. 1989

Faculty consultants:
- Prof. A. Bryson, Jr. (controls)
- Prof. J. D. Powell (controls)
- Prof. B. J. Cantwell (fluid mechanics)

Professor Roberts provides overall coordination of this program, which is centered in the Department of Aeronautics and Astronautics.

Appendix A

Bifurcating Air Jets at Higher Subsonic Speeds

D.E. Parekh and W. C. Reynolds

Presented at Sixth Symposium on Turbulent Shear Flows
Toulouse, France, September 1987

BIFURCATING AIR JETS AT HIGHER SUBSONIC SPEEDS

D. E. Parekh and W. C. Reynolds
Stanford University

ABSTRACT

Dual-mode, dual-frequency acoustic excitation of round air jets is described. The jet evolution and structure is documented by flow visualization at velocities up to 75 m/s and Reynolds numbers to 100,000. The ratio of the axial to helical excitation frequencies is exactly two. This type of forcing causes the jet to spread dramatically in one plane. The spreading angle increases with excitation amplitude to angles as high as 70 degrees.

INTRODUCTION

The sensitivity of jets to sound has fascinated researchers for many decades. Brown demonstrated that laminar jets develop vortex structures and increase in spreading angle in response to acoustic excitation at various critical frequencies (1). Most current work focuses on jets consisting of an axisymmetric shear layer and a potential core. In this case the shear layer rolls up to form distinct vortex rings unlike the laminar jets of Brown which form vortex structures comprised of the entire jet stream.

The vortex-formation frequency can be fixed by axial excitation. This single-mode forcing can control jet growth by enhancing or suppressing vortex pairing (2,3). The "collective interaction" of several vortices due to subharmonic forcing has been demonstrated in mixing layers (4). This type of forcing has also been applied to high speed jets (5) and jets issuing from asymmetric nozzles (6).

The study of excited jets has involved multiple-frequencies and multiple-modes. A study of active cancellation of pure tones in jets involved simultaneous perturbations at two frequencies (7). Other work has focused on the changes in initial shear layer development in response to multiple-frequency forcing (8).

Properly combining axial and first-order helical modes can dramatically alter the structure and momentum transport of round jets. This type of *dual-mode* forcing can cause a jet to split into two distinct streams when the ratio of the axial to helical frequency is two. These phenomena occur only within a small range of Strouhal numbers, and within that range the spreading angle increases with St. These dramatic changes in jet development were discovered in a study of mechanically-perturbed round water jets at a Reynolds number of 4,000 (9). Similar jet development was observed in acoustically-excited air jets in the Reynolds number range of 10,000 to 20,000 (10).

This work extends the study of bifurcating air jets to Re of 100,000. Since the apparatus described in Ref. 10 is inadequate to produce the high levels of excitation required at higher velocities, a new acoustic excitation system was developed. The response of the jet at various Reynolds numbers is visually documented.

EXPERIMENTAL APPARATUS AND APPROACH

Flow System

The experimental apparatus is shown schematically in Fig. 1. Air flows through a porous bronze cylinder into the plenum and out through a 2-cm-diameter nozzle. The two-piece nozzle has a carefully machined fifth-order polynomial profile with zero slope at inlet and exit. The transition from the lower to the upper half of the nozzle occurs at the inflection point of the profile. The area contraction ratio is 25 to 1, and the length-to-diameter ratio is 5.

The jet exit is positioned in the center of a 60 cm x 60 cm flat panel and is flush with this panel. Baffles made of particle board and Sonex acoustical foam surround the jet on all four sides. These baffles are located 1 m from the jet on each side. The fume hood located 1.3 m above the jet is lined with Sonex foam. Entrained air flows into the test cell through the 0.8-m gap between the baffles and the floor.

Flow Visualization

A small 0.5-mm annular gap between the two halves of the nozzle provides a passage for injecting a fluid marker into the boundary layer. In these experiments cigar smoke serves as the fluid marker. The smoke enters the nozzle assembly through four ports and passes through a honeycomb ring prior to merging with the core flow. The smoke is injected tangential to the main flow at a flow rate equal to 2% of the total flow rate. This value approximately corresponds to the ratio of the gap area to the nozzle's cross-sectional area at its inflection point.

A 10-watt, copper-vapor, pulsed laser is focused into a 1-mm sheet to illuminate cross-sections of the jet. Both instantaneous and phase-averaged pictures of the flow are taken. Instantaneous pictures are achieved by triggering the laser to fire one 30-ns pulse per exposure taken with a 35-mm camera. By triggering the laser with the excitation signal and using multiple pulses per exposure, one obtains phase-averaged images. The number of laser pulses (N) per phase-averaged picture ranges from 8 to 32 and in each case the helical signal triggers the laser pulses.

Acoustic Excitation

Since high levels of acoustic power are needed, 120-watt compression drivers (JBL 2485J) are used. One driver located at the bottom of the plenum provides the axial excitation. The four drivers surrounding the jet are connected by 2-cm steel tubes to the four separate passages surrounding the jet exit.

The acoustic excitation consists of two modes and two frequencies. The frequency of the axial mode is exactly double that of the helical mode. The helical mode is achieved by feeding sine waves of equal frequency and amplitude but different phase into the four external drivers. The signal of each driver differs from that of an adjacent one by 90 degrees and from that of the opposite one by 180 degrees. The axial signal can be introduced separately through the internal driver or added to the helical-mode signal. In the second case the internal driver is not used. In both cases the relative phase of the axial and helical signals is variable.

The sound pressure levels of the axial (A) and helical (H) excitations are measured with a 6.4-mm condenser microphone (B & K 4136) positioned 2 cm above the jet exit and 1 cm from the jet centerline. The microphone is parallel to the horizontal plane and points toward the jet centerline. All measurements are made with no flow, and the two modes of excitation are measured separately. The helical excitation amplitudes that are reported are those resulting from all four drivers.

RESULTS AND DISCUSSION

This work extends the application of dual-mode excitation to higher speeds. The mean exit velocities are 19 to 75 m/s, which correspond to exit-diameter Reynolds numbers of 25,000 to 100,000. Preliminary investigations confirmed previous results that demonstrate an increase in spreading angle with Strouhal number (St) up to St = 0.6 (9,10). In all cases discussed here, the Strouhal number is based on axial frequency, exit diameter, and mean velocity and has a value of 0.55. This choice of Strouhal number corresponds to excitation frequencies in the range of 250 to 2000 Hz.

The axial excitation may be introduced through either the internal or external drivers. However, at the lower Reynolds numbers, introducing the axial excitation through the internal driver sometimes results in separation inside the nozzle. This separation is evident as streaks of smoke present as far as a few tenths of a diameter from the nozzle wall at the jet exit. This phenomenon seems to be due to an interaction between the sound field and the shear layer produced at the injection interface. Thus, the axial excitation is channeled through the internal driver only in the Re = 100,000 case.

The axial excitation causes the shear layer to form large vortex rings at the same frequency as the excitation (Fig. 2). The shear layer initially forms small, closely-spaced rings which subsequently combine to form the large vortex rings. This is an example of the "collective interaction" mechanism discussed by Ho and Huang (4). The instantaneous cross-section in Fig. 3 shows the jet response at Re of 25,000 to the helical mode alone. The potential core exhibits a wavy shape and the shear layer develops asymmetrically. However, no pronounced increases in spreading angle are evident at this forcing amplitude. When both axial and helical modes are added together, the character of the jet changes significantly even at modest excitation amplitudes (Fig. 4). The jet spreads at a wider angle and adjacent vortex rings tilt in opposite directions.

Two unexcited jets at Re of 50,000 and 100,000 are presented in Figs. 5 and 6. The shear layer appears to be initially laminar but quickly turns turbulent in both cases. The jet spreading angle is very moderate. As seen at Re of 25,000, axial forcing causes the periodic formation of ring structures (Fig. 7). The large changes in scale as the rings grow and combine is very evident even though this picture is a phase-average of 32 different realizations. The asymmetric ring trajectories resulting from dual-mode excitation result in smoke reaching the jet centerline about one diameter closer to the jet exit (Fig. 8).

An axially-excited jet at Re of 100,000 is shown in Fig. 9. The high level of forcing causes the shear layer to turn turbulent at the exit. At low levels of excitation (below 120 dB), the shear layer remains laminar for the same distance as in the unforced jet (Fig. 6). As previously discovered (10), the spreading angle increases with excitation amplitude to angles as high as 70 degrees (Figs. 10 and 11). At the lower Reynolds numbers, increasing the helical excitation amplitude beyond a certain level does not increase the spreading angle and in some instances seems to reduce it. This is true regardless of how the axial excitation is introduced. The excitation levels required to reach this saturation level is found to increase with Reynolds numbers.

Adjusting the phase between the axial and helical signals rotates the plane in which the jet bifurcates. By rotating the jet such that it bifurcates in the plane perpendicular to the light sheet, one obtains the image in Fig. 12. Since the jet fluid moves away from this bisecting plane, the smoke density along the jet centerline decreases rapidly. The striking difference between the cross-sections in Figs. 10 and 11 demonstrates the fact that the bifurcating jet spreads rapidly in one plane rather than axisymmetrically.

CONCLUSIONS

The effect of combined axial and helical excitations on the development of round, turbulent air jets has been studied by flow visualization. Setting the axial frequency at exactly double the helical frequency causes the jet to spread rapidly in one diametrical plane. Increasing the amplitude of the helical excitation results in spreading angles as high as 70 degrees. However, increases above a certain level do not further amplify the spreading angle. Higher levels of excitation are required to reach this saturation level at higher Reynolds numbers. This work demonstrates that dual-mode forcing can cause jets to bifurcate at velocities up to 75 m/s and Reynolds numbers up to 100,000.

ACKNOWLEDGMENTS

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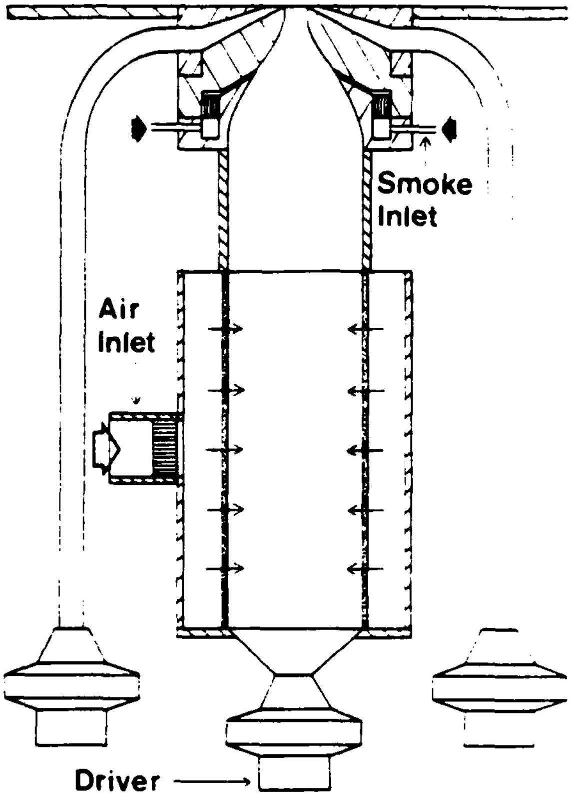

Figure 1. Schematic of jet facility.

Figure 3. Helically-excited jet at Re = 25,000 (N = 8).
H = 91 dB

Figure 2. Axially-excited jet at Re = 25,000 (N = 8).

Figure 4. Bifurcating jet at Re = 25,000 (N = 32).
H = [illegible] dB

Figure 5. Natural jet at Re = 50,000 (N = 32).

Figure 7. Axially-excited jet at Re = 50,000 (N = 32).

Figure 6. Natural jet at Re = 100,000 (N = 8).

Figure 8. Bifurcating jet at Re = [illegible] (N = 32 [illegible]

Figure 9 Axially-excited jet at Re = 100,000 (N = 8) A = 130 dB

Figure 10 Bifurcating jet at Re = 100,000 (N = 8) A = 130 dB and H = 124 dB

Figure 11 Bifurcating jet at Re = 100,000 (N = 8) A = 130 dB and H = 118 dB

Figure 12 Bifurcating jet at Re = 100,000 (N = 8) [illegible] A = 130 dB and H = 118 dB

ERRATA

1. Page 3: "Figs. 10 and 11 demonstrates" should be "Figs. 10 and *12* demonstrates."

2. Page 4: "Figure 4. . . . (N = 32)" should be "Figure 4. . . (N = *8*)."

Appendix B

Automatic Control of Acoustically Excited Jets

C. R. Koch, J. D. Powell, and W. C. Reynolds

Prepared for AFOSR Workshop on Unsteady Separated Flows
Colorado Springs
July, 1987

Automatic Control of Acoustically Excited Air Jets

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Introduction

The subject of research to be discussed is: Automatic Control of Acoustically Excited Air Jets. The purpose of the research is to try and understand the automatic control problems as they pertain to a complex fluid dynamical system. This is a relatively new field called flow control, which is a combination of control theory and fluid mechanics. A brief background on the fluid mechanics and control systems, as well as a discussion of the current research, and future work will be undertaken.

Background

Fluid Mechanics

The fluid mechanics of an axially excited jet is quite complex, yet it is fairly well understood, making this flow field an ideal candidate for an attempt at closed loop control. A brief qualitative description of the flow will be given next.

Equipment

The experimental apparatus for studying the excited jet is shown in figure 1 which shows how the air travels through the plenum and out the nozzle[1]. The speakers in the axial and transverse direction are driven by properly phased sine wave signals. This provides dual mode - axial and transverse - excitation to the air jet. From a control theory perspective, the speakers are the actuators by which one can control the plant (the flow field downstream of the nozzle exit).

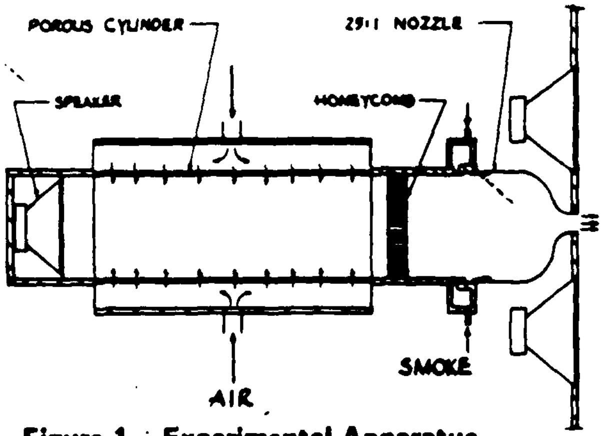


Figure 1 - Experimental Apparatus
from [1] by permission

Vortex Rings

Large changes in the flow field from the natural or unexcited jet can be obtained using relatively little excitation with the speakers. A schematic of several remarkable excited flow states is shown in figure 2.

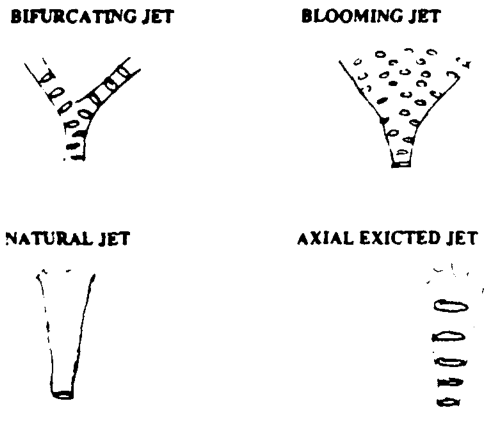


Figure 2 - Jet Schematic

The rings shown in figure 2 are vortex rings, and they are the key to understanding the flow field. A vortex ring is formed by the shear layer between the fast moving jet air and the relatively slow moving room air. That is, the viscosity of the fluid, air in this case, causes a shear stress on the fluid in the region of relative motion which in turn cause the fluid to roll up in a circular ring, a vortex ring.

Natural Jet

In a natural jet, one with no acoustical excitation, the formation of vortex rings is irregular with time. This results in some vortex rings, which start at the nozzle exit close together, to coalesce. Other vortex rings which are sufficiently far apart do not coalesce. The result is a turbulent jet with time varying small turbulent structures and time varying large structures (vortex rings in this case)[1].

Axial Acoustic Excitation

In an axially excited jet, the acoustical excitation comes from the axial speaker only. Methods other than speakers such as resonating cavities can be used to axially excite a jet. A relatively small acoustical excitation causes the vortex rings to be formed at the acoustical excitation frequency. The axial excitation triggers a uniform (in time) spaced train of vortex rings to be formed at the nozzle exit.

Dual Mode Acoustic Excitation

In the dual mode excited jet, both the axial and orbital acoustical excitation are used. A small perturbation[3] (15% and 4% of the jet exit velocity for the axial and orbital direction respectively) causes a large change in the flow field. Vortex ring interaction is the key to understanding how the flow field changes from the natural state, to the dual mode excited state. The idea of the acoustical excitation is this: 1) the axial excitation forces a regularly spaced train of vortex rings and concentrates the vorticity in these rings, the rings are formed at the frequency of the axial speaker; 2) the orbital excitation perturbs the vortex ring at the nozzle exit, which interacts with the other vortex rings further downstream according to the Biot Savard law for thin filament vortices[3]. The vortex rings tilt each other.

Important Parameters

When R, the ratio of axial to transverse frequency is two for example, odd numbered vortices are perturbed one way (perpendicular to the jet axis) while even numbered vortices are perturbed the other way. This causes a bifurcating jet (the jet splits into two branches) if the jet is in the proper region in a Strouhal Number phase plane plot - more on this later. When R is equal to 3 the jet trifurcates or splits into three branches. Non-integer values of R from 1.7 to 3.5 cause the vortex rings to go in all directions. This is called a blooming jet because the vortex rings look like a flower blooming. The fluid dynamical model of the jet using vortex ring interaction model has been verified both experimentally and by computer simulation[2,3].

The jet will only go into the excited or high mixing state if the the parameter R (axial to transverse frequencies) and the axial Strouhal number is in an experimentally determined range[3] (Axial Strouhal Number - STax=Fax*D/U is the non-dimensionalized axial frequency, by jet exit velocity and jet exit diameter). The excited region is shown in an axial vs transverse phase plan plot in figure 3. One would expect the Strouhal number to be important because it is measure on how far apart successive vortex rings are. When the axial Strouhal number is high, above approximately 0.7 the vortex rings are close together so they get tangled up rather than tilting each other. When the axial Strouhal number is low the vortex rings are relatively far apart and since the induced velocity of one ring on another follows the Biot Savard Law which falls off as an inverse square of distance, the tilting of the rings is small[3].

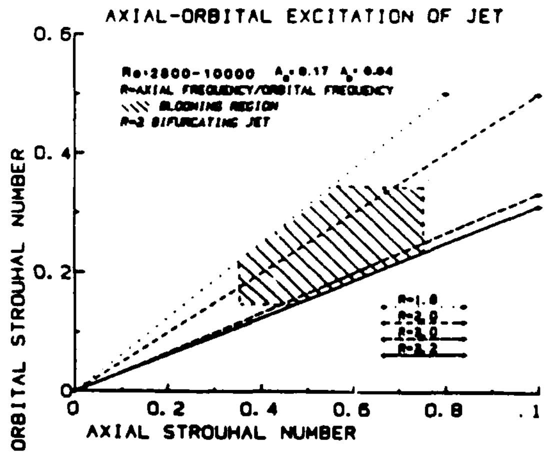
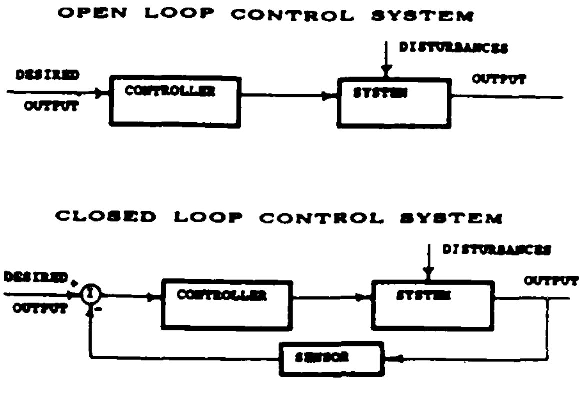


Figure 3 - Phase Plane Plot
from [3] by permission

Controls

General

Now turning to some general concepts in the area of controls. The two types of control systems that will be discussed are open and closed loop control. A schematic of open versus closed loop control is shown in figure 4.



Advantages of Feedback

1. Less Sensitive to Changes in the System - or Plant
2. Less Sensitive to Disturbances
3. Speed of Response/Stability can be Improved

Figure 4 - Open vs Closed Loop Control

In this case the jet flow field is the system, the controller is the logic determining the speaker frequency, amplitude and phase, the actuators are the speakers, and the disturbances are the jet exit velocity and velocity disturbances to the jet flow field.

Closed loop control systems have many advantages over open loop control systems. Three major advantages of closed loop control are: 1)Less sensitive to changes in the system or plant; 2)less sensitive to disturbances; 3)speed of response/stability can be improved. Closed loop control requires sensors to provide a feedback signal.

Sensors

The sensor(s) in a closed loop control system (figure 4) must be such that they allow the controller to characterize (observe) the system. That is, the modes of the system that are of interest must be observable and non-observable modes should be stable. For example, placing a position sensor at the node of a vibrating beam yields no information about that particular vibrating mode making that mode unobservable with that particular sensor. Placement of sensors in the flow field of the acoustically excited jet for closed loop control is one of the more difficult aspects of the current investigation.

Current work

General Objectives

The first stage of the research is to implement an open loop control system. That is, for changing flow speeds hold the jet at a particular point in the Strouhal number phase plane (Figure 3) by changing the frequencies in the axial and transverse direction.

The aim of the open loop control is : 1) to gain an understanding of some of the problems that will be encountered - such as equipment, and software; 2) to automate (computerize) the inputs and outputs of the system so a high speed closed loop controller can be implemented.

Original Apparatus

The original jet apparatus required complete manual adjustment at each steady operating point. Note - the jet is open loop stable and very robust to disturbances so it is possible to manually dial up the desired operating point.

Existing Apparatus

The first stage of open loop control was to add a sensor to measure the jet exit velocity or flow speed. To determine the flow speed, the stagnation pressure in the plenum is measured and the jet exit velocity is deduced. An Omega piezo-resistive 0 - 10 in. of H2O pressure transducer is used. The range of flow velocities that obtainable with the current experimental rig are 3 - 30 m/s. The system was automated using an IBM AT computer and a data translation DT2821-F digital and analog I/O board. The frequencies and amplitude of the sine wave signals that actuate the speakers can be controlled using function generators (HP 61014A) set on a nominal value and using the VCO - voltage controlled oscillator, and by the AM - amplitude modulation inputs. This was in fact done for the frequency only and not for the amplitude because the effect of amplitude on the jet has not yet been completely investigated . The resulting system was built and resulted in a system in which the jet flow rate could be changed and the open loop control program would schedule the frequencies to hold the jet at a given R and STax. Two problems were encountered. One, the pressure transducer needed to sampled for several cycles of axial frequency in order to yield a satisfactory average of jet velocity. This problem can be easily solved by a low pass filter. The second problem was that the phase shift circuit that is used to give the 90 degree phase shift between successive transverse speakers is frequency dependent. This requires manual adjustment of the phase shift electronics when there are large changes in jet flow rate and in excitation frequency. The phasing problem is more difficult to solve and a phase locked loop (PLL) was designed. The pull in frequency range (how far the unlocked frequency can be from the reference frequency and still lock into the reference) was found to be unacceptable in the PLL circuit.

The apparatus is now being modified to be completely open loop controlable. To do this the electronics are completely automated. The electronics have been changed by changing how the sine wave signals which drive the speakers are generated. The sine waves are going to be generated by a ROM look up table external to the IBM control computer to avoid the overhead of servicing this function. Instead the IBM will interface to the external sine wave generator resulting in much less computation overhead.

In addition, a shroud has been added for several reasons. One, a shrouded jet is a interesting problem with practical applications to jet ejectors and thrust augmenters. Two, there is a simple performance parameter that can be measured - entrained air - which can be maximized in an optimal control algorithm. In order to measure entrained air a flat surface is desirable which is one reason why the speakers were enclosed. The other reason for enclosing the speakers is to concentrate the speaker energy at the nozzle exit where it is the most effective. The third and final reason for adding a shroud is that it provides a convenient platform on which to mount sensors in the flow, that will be used in the next stage of the investigation to provide a feedback signal.

Work Remaining

The work in the immediate future is to complete construction of the shrouded apparatus. This apparatus will be used as a vehicle to test out control algorithms which are developed by theoretical considerations and experimental system identification techniques. Eventually a control algorithm will be developed. At this stage, the utility of closed loop control for this system is unclear because the jet is open loop stable and robust to disturbances. Perhaps one objective of closed loop control is for a burning jet. To date, in a burning (methane), the acoustical excitation seems to have no effect on the jet. That is, the excited state of the jet can not be obtained using a manual open loop control scheme. Perhaps closed loop control would provide a means to hold the burning jet in an excited state. However a burning jet is a very difficult control problem because even the fluid mechanics is not well understood. A more realistic approach would be to use closed loop control to filter out simulated disturbances. The simulated disturbances could model the combustion process, with the disturbance model becoming more and more complex (and realistic) as an understanding of the control problems is gained.

Summary

Substantial progress has been made. The control electronics have been updated from completely manual to partially automated with a completely automated configuration in the design / construction phase. A shrouded configuration for the jet was decided on and is being constructed. The redesign was done from both a fluid mechanical and a control theory perspective which will allow for substantial advances in the next year.

Acknowledgments

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Appendix C

Control of Vortical Flows over a Delta Wing

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THE CONTROL OF VORTICAL FLOWS OVER A DELTA WING

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ABSTRACT

A research program to examine active control of vortical flows over delta wings at high angles of attack has been initiated. A thin tangential wall jet, exiting at the rounded leading edge of a delta wing, is used to control the primary separation of the cross flow and hence to control the equilibrium of the lee-side vortices. Initial experimental results using a high speed ramp change in the blowing momentum of the jet suggest that this technique will be suitable for development as an active control. Initial results from a simple analysis have also served as an aid in the interpretation of the experimental results. The present paper is in part a report of the progress in establishing an unsteady vortex control experiment and a parallel control system analysis.

NOMENCLATURE

b	wing semi-span
C_N	wing normal force coefficient
C_p	pressure coefficient
$C\mu$	blowing momentum coefficient
y,z	spanwise, normal coordinates
α	angle of attack
δy	position of displaced separation relative to leading edge
δz	position of displaced separation relative to wing chord plane

INTRODUCTION

Advanced aircraft configurations of delta wing planform, even at moderate angles of attack, experience significant asymmetries in the vortical flow over the wing upper surface, including the so-called vortex bursting, due to asymmetries in forebody geometry or slight yaw. At high angles of attack the vortex flow ceases to be steady and well organized and is replaced by unsteady shedding with a consequent significant loss of lift. In light of these problems there is a strong interest both in understanding vortical flows associated with aerodynamic lift and in devising an approach to regulate or actively control them. This paper describes a method to directly affect the vortex flow field over a delta wing by controlling the boundary layer separation near the leading edge of the wing using a wall jet.

Although this research leading to the active control of wing vortex aerodynamics is only in its initial stages, sufficient progress has been made to point the way toward an approach to vortex control that should eliminate unwanted flow asymmetries at low angles of attack and create steady, organized flow at high angles of attack. Further work is required to demonstrate the feasibility of active control for various specific applications such as the control of wing rock or post-stall maneuvering and research in this direction will be undertaken as part of the future program.

Description of the Flow

The flow considered is that over a delta wing at angle of attack. Separation occurs in the vicinity of the leading edge forming vortex sheets which feed a pair of vortices lying above the wing. For a rounded leading edge (in contrast with a sharp leading edge) the location of separation is determined by the adverse pressure gradient near the leading edge on the upper surface. Figure 1 gives a simplified description in the cross-flow plane illustrating the vortex and its feeding sheet, reattachment and the secondary structure formed by the confluent boundary layer starting from the lower and upper stagnation lines.

Inasmuch as the equilibrium of the entire flow field is determined by the primary boundary layer separation it should be possible to control the flow field (i.e. the location and strength of the vortex and its feeding sheet) by controlling the location of that separation; moreover, it is expected that such an approach would be very effective in that a relatively small momentum change in the boundary layer will have a large influence on the strength and position of the resulting vortex.

In the present work this momentum change is accomplished through the use of a thin wall jet placed along the leading edge and blowing tangentially inward. The jet energizes the boundary layer as it flows around the leading edge and across the upper surface of the wing, figure 2. The wall jet is more robust than the original boundary layer and remains attached to the rounded leading edge by the Coanda effect. This causes a delay in separation which in turn influences the entire flow field. The vortex and its feeding sheet must relocate and the vortex strength is modified such that equilibrium is maintained.

By measuring changes in the pressure distribution on the wing surface and using this information to regulate the blowing strength (i.e the momentum coefficient) of the wall jet, it should be possible to control the location of the vortices and thereby control any asymmetries Rolling moments may be produced or the lift modified, independent of angle of attack.

The analysis and experiments described in the following sections represent the first attempts to understand more completely this approach to vortical flow control, to provide some basic information that will lead to the formulation of control laws, and to assess the effectiveness of this approach to aerodynamic control at high angles of attack.

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ANALYSIS

The methods used here to analyze the flow over the delta wing are approximate and have been chosen over more accurate but more complex methods in order to identify the parameters of primary importance and enhance the interpretation of the experimental results. The initial analysis assumes that the inviscid flow will respond instantaneously to the change of location of the vortex sheet due to the momentum of the wall jet. This analysis will be improved subsequently to incorporate unsteady effects with wall jet blowing using a modified vortex-lattice method.

For the present, the analytical approach used to represent the flow is that first used by Brown and Michael[1] modified to allow for a rounded leading edge and an arbitrary placement of the vortex separation line as shown in figure 3. A pair of planar vortex sheets is assumed, whose strengths increase linearly with distance downstream, consistent with conical symmetry, and which feed a concentrated vortex pair in the flow above the surface.

This configuration is analyzed in the cross-flow plane using conformal mapping methods to solve a two-dimensional problem, while taking into account the three dimensional nature of the flow by applying a force free condition on the vortex system. From this analysis the pressure distribution (and the forces and moments) on the wing are determined when the location of the separation lines are assumed. This pressure distribution is used in the calculation of the turbulent boundary layers on the upper and lower wing surfaces starting from the stagnation points of the cross-flow and continuing to the separation points (a viscous analysis which accounts for the three dimensional nature of the boundary layers is used). The fact that the pressure at these points is assumed to be equal (implying that the secondary flow is weak) provides a condition which is used to correct the location of the vortex feeding sheet separation that was previously assumed. This gives a unique solution for flow over the wing in the absence of blowing into the boundary layer.

The influence of blowing is represented by replacing the boundary layer near the leading edge by a wall jet whose strength is characterized by a momentum coefficient. The wall jet separation is governed by a similar condition to that of the turbulent boundary layer but requires a much larger pressure gradient at separation. Thus the vortex sheet is displaced inboard and the entire inviscid flowfield is modified. The vortex displacement is determined by again equating the surface pressures at the cross-flow separation points (for the wall jet and upper surface boundary layer) and in this way relationships between the blowing momentum coefficient and the inviscid flow field parameters (vortex position, vortex strength etc.) are established. In general it is found that tangential leading edge blowing will reduce the magnitude of the vortex-induced lift but increases that due to leading edge suction.

$$\frac{\text{Vortex Lift}}{\text{Unblown Vortex Lift}} = \left(1 - (\delta y/b)^{0.5}\right)^{n}$$

where $n \approx 3$ for a flat plate, ≈ 2.6 for a 10% ellipse

These observations are based on a very simple theoretical model which may not be sufficiently accurate to be used as a basis for control laws; however the results reflect the physical mechanism by which the wall jet provides separation control in a qualitative way and give insight into the experimental results. Improved methods of calculating the flow field with sufficient accuracy including the effects of the trailing edge are currently under development.

The purpose of the improved method of analysis is to provide a simulation of the unsteady aerodynamics of a wing, including the effects of blowing in a typical maneuver. The method must be computationally fast and efficient inasmuch as the results will be used to provide the logic for the control algorithm.

The basic aerodynamic model is a low order vortex-lattice method. The wing is represented by panels having concentrated vorticity around the perimeter, figure 4. The flow separates from both the leading and trailing edges and the separated sheets are modelled as vortex rings that evolve in a time accurate way under the influence of the flow computed at a previous time step and the motion of the wing. The separation lines are taken to be at the leading edge in the absence of blowing.

In the presence of blowing two effects must be taken into account in this model, namely:

a) movement of the separation line inboard from the leading edge

and

b) additional suction near the leading edge due to the centrifugal action of the wall jet.

These effects will be reflected as changes in the amount of vorticity shed into the free sheets and will ultimately influence the forces and moments on the wing.

The work will first consider the range of angle of attack below that corresponding to the point of maximum normal force for which the flow is generally well organized. It is hoped that with strong blowing, which helps retain organized flow to higher angles of attack, this model may still give reasonable results.

EXPERIMENT

Previous Work

The concept of tangential leading edge blowing (TLEB) has previously been examined for the case of steady blowing only. Details of the experimental configuration are contained in reference 2 and, together with reference 3, describe some of the more interesting observations of the effects of TLEB on the vortical flow over a delta wing at high angle of attack. A brief summary of some of the basic performance characteristics is now presented.

The model under test, figure 5, was a semi-span delta wing with 60 degree leading edge sweep; the blowing slot extended over approximately 70% of the leading edge. The model was designed to be as near conical as possible and consequently the slot gap and the wing thickness increased linearly from the apex of the wing. The normal force results were obtained from integration of surface pressure measurements over the chordwise extent of the jet. The Reynolds number based on the root chord was approximately 7×10^5. Figure 6 shows the effects of TLEB on the overall wing normal force as a function of angle of attack. Two different regimes can be observed. The first, at angles of attack below the point of maximum normal force, (referred to as low angle of attack) indicates that the blowing has little or no effect on normal force. The second, at angles of attack beyond the point of maximum normal force, (referred to as high angle of attack) indicates that a significant amount of force augmentation is produced. Note that the increment in normal force is 10 to 20 times the increment in blowing momentum, where the momentum represents the gain in normal force if the jet were used as a pure thrusting device. Further information regarding the similarity of these two regimes can be obtained from examination of the spanwise pressure distributions for both low and high angles of attack.

Figure 7 illustrates the effect of TLEB on the spanwise pressure distribution for the low angle of attack condition. It is obvious that the condition of nearly constant normal force arises from a cancellation of two opposite effects. As the blowing momentum is increased, the point of cross-flow separation moves around the leading edge and a region of high suction is created under the attached wall flow. At the same time, the influence of the vortex appears to diminish and the location of the peak vortex-induced suction relocates inboard. It is simple to demonstrate experimentally that in the limit, the crossflow separation point can be relocated all the way to the wing root thereby eliminating any vortical flow. For that case the pressure distribution conforms to that expected from the 'R.T. Jones' or 'attached flow' cases. It is important to note that the primary effect of TLEB at low angles of attack is to reduce the strength of the vortical flow and relocate the vortex inboard while maintaining nearly constant wing normal force.

Figure 8 shows the effects of TLEB on the spanwise pressure distribution at high angles of attack. Observe, that initially with no blowing, no vortical flow is apparent from the pressure distribution. The flat distribution on the upper surface suggests a separated flow over the entire span of the wing. For the smallest increment in blowing momentum illustrated, the first effect of TLEB at high angles of attack is to recreate the vortical flow over the wing upper surface. This causes a corresponding large increase in the normal force. Flow visualization studies have also indicated a strong stabilization of the flow. As the blowing momentum is increased the augmentation of the vortical flow and the normal force reaches a maximum beyond which a lateral movement of the vortex, coupled with a decrease in the vortex strength, is observed. This corresponds exactly to those effects observed at low angles of attack. Recognizing that for any geometrical angle of attack, in the absence of blowing, there exists a unique vortex strength and location. Then the concept of an 'effective' angle of attack of a vortical flow may be proposed. The effect of TLEB may be thought of as reducing the 'effective' angle of attack that the vortical flow represents. In the limit the fully attached flow case for a given geometrical angle of attack represents a vortical flow with an effective zero angle of attack.

Objectives of the Present Program

The experimental objective is to determine the effectiveness of TLEB in providing active control of a vortical flow over a range of angles of attack. To obtain the information necessary for the eventual development of control laws for TLEB it was required to determine the time constants associated with the restructuring of the vortical flow. Sensor types and locations to act as feedback or feedforward inputs to the control system also had to be determined. There were 3 inter-related capabilities that needed to be developed in order to achieve the objectives. Those capabilities were: a fast optical scanning laser light sheet system, an unsteady blowing control mechanism, and an unsteady surface pressure measurement system.

Laser Light Sheet System In order to obtain visual perception of the transient effects of TLEB, a fast scanning image processing system has been developed. This consists of scanning a laser light sheet through the flow of interest, the laser being pulsed at rates which effectively freeze the flow structure. The images produced can be recorded on a high speed camera which is synchronized with the light pulses. The recorded images may then be digitized, processed and assembled to provide a three-dimensional image of the vortex structure. This information should clearly show how the jet flow affects the trajectory and strength of the feeding sheets and the vortex core. Since the pulse width of the laser is small (30nS), an extremely high powered laser is required to provide sufficient illumination of the flow. A Copper Vapor laser has been acquired for this purpose and is presently undergoing installation into the wind tunnel area. A suitable optical arrangement for scanning the sheet down the axis of the vortex has been developed and is also being installed.

Unsteady Blowing Control To provide the transient blowing, a pneumatic control system had to be developed. It was decided that a simple ramp change of internal pressure was the most practical form of control, both from pneumodynamic and time constant derivation considerations. It was anticipated that multiple time scales would be present, some of which could be related to the downstream convection of the wing wake. Sinusoidal or other periodic variations of pressure would tend to obscure these effects. A simple rotary solenoid system has been fabricated with a custom built switching power supply which enables operation of the solenoid at rates of 9000 degrees/second. It was found that the optimum configuration of the solenoid in the supply line was as close to the model plenum as possible, figure 9. The solenoid controlled a bleed flow that corresponds to the change in pressure required in the plenum. In addition, an upstream air bleed was included, which, when coupled with a simple manual flow control valve, provided sufficient control over both the initial and final pressure levels in the model plenum. A ramp time of the order of 4 milliseconds has been achieved with little or no overshoot in the pressure.

Surface Pressure Measurement To correlate the flow visualization and the transient loads on the wing it was required to measure the unsteady surface static pressures. A data acquisition system has been assembled which is capable of operating the blowing control system and sampling a maximum of 16 channels of analog information with an aggregate sampling rate of 160 Khz. Kulite miniature pressure transducers will be mounted in the surface of the new model and will provide real time records of the changes in the vortex influence on the wing surface. Each channel will be simultaneously sampled at 10 Khz over a total time of 6 seconds. These results should provide accurate measurements of the time constants and phase relationships involved in TLEB.

Wind Tunnel Model The original model that was used to determine the feasibility of TLEB was designed to be geometrically conical. This proved to be an unnecessary complication and for the present effort a new semi-span model has been produced, figure 10. A semi-span configuration has again been chosen for simplicity of construction and relative scale in the test section. The wing is of constant thickness and has a 50 degree leading edge sweep. The trailing edge is closed to a point by the inclusion of a simple dual flap system which may be later used to determine the improved effectiveness of mechanical flap devices in the presence of TLEB. The leading edge slot extends over most of the leading edge and the slot gap can be varied by replacement of the leading edge cylinder. The model can be configured for either unsteady or steady pressure measurement or a combination of both. Model fabrication has been successfully completed.

Experimental Program

The assembly and validation of all the components of this program should be completed on schedule by the end of the first year of the program. Initial steady state testing of the new semi-span wing (October 87) will include measurement of the blown/unblown vortex influence and flow visualization using an existing CW laser light sheet system and video camera.
Having confirmed the operation of the model and support systems, initial scanning light sheet images will be obtained for a selection of predetermined conditions. These conditions will also be examined in some detail using the unsteady surface pressure measuring system and the correlation of the results will provide initial information on the time scales associated with TLEB. This information will provide the initial input for the formulation of control laws for the active control of vortical flows.

CONCLUDING REMARKS

An ambitious research program to determine the effectiveness of tangential leading edge blowing in providing active control of vortical flows has been initiated. Simple analytical techniques have been used to gain insight into the interpretation of previous steady state experimental results. Analysis of the time dependent problem is being pursued using a vortex lattice technique. All the required experimental systems have been assembled and are awaiting initial testing. A new wind tunnel model has been designed and fabricated and is capable of providing both steady and unsteady surface pressure measurements in the presence of transient blowing momentum. In the coming year, initial results for the time scaling of the response of the vortical flow to changes in blowing momentum will be obtained and this will provide input for the initial formulation of control laws.

REFERENCES

1. Brown, C.E. and Michael, W.H. 'On Slender Delta Wings with Leading Edge Separation' Journal of Aeronatical Sciences, Vol 21, 1954.

2. Wood, N.J. and Roberts, L. 'The Control of Vortical Lift on Delta Wings by Tangential Leading Edge Blowing' AIAA paper 87-0158, Jan 1987.

3. Wood, N.J., Roberts, L. and Lee, K.T. 'The Control of Vortical Flow on a Delta WIng at High Angles of Attack' AIAA paper 87-2278, Aug 1987.

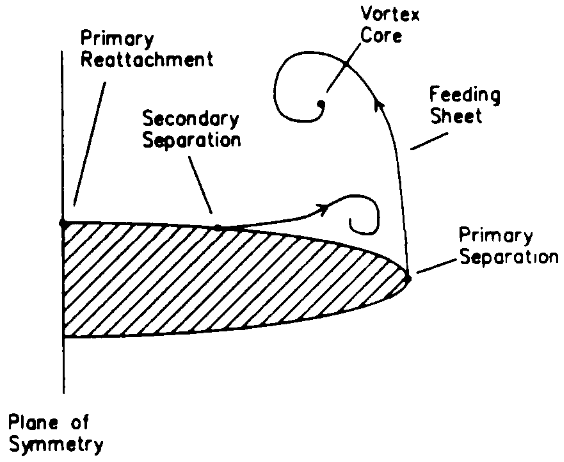

Figure 1: Flow in the Cross-Flow Plane of a Delta Wing at Angle of Attack.

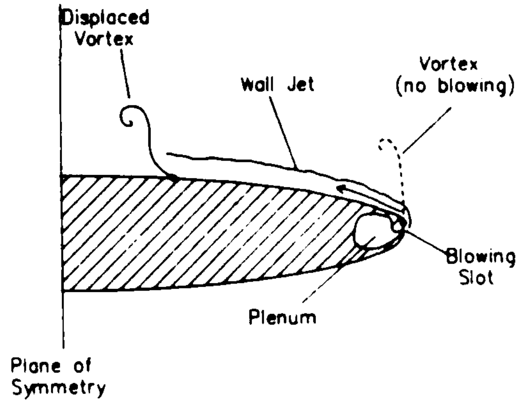

Figure 2: Tangential Leading Edge Blowing Configuration.

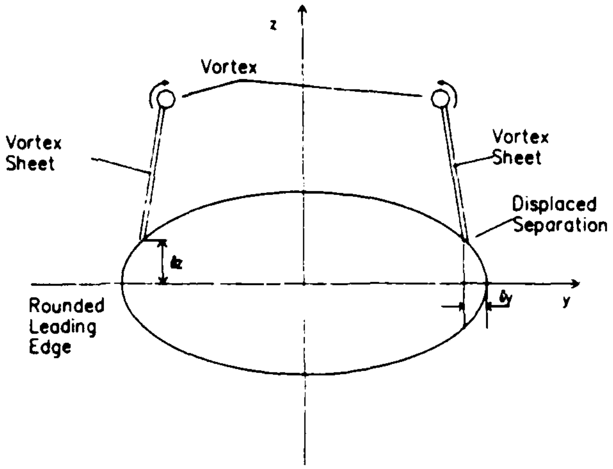

Figure 3: The Modified Brown and Michael Model.

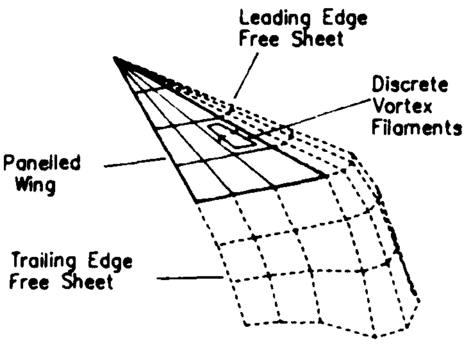

Figure 4: The Vortex–Lattice Method.

Root Chord = 27.9 cm, L.Edge Sweep = 60 degs

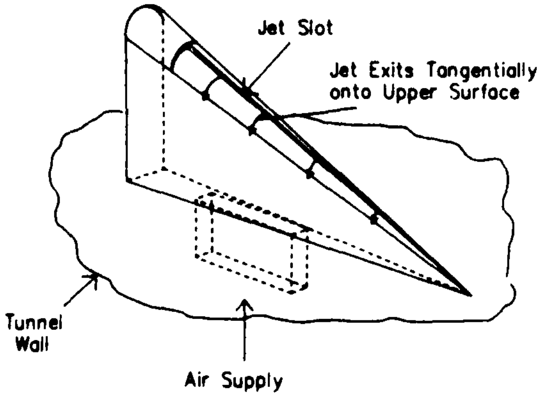

Figure 5: Original Wind Tunnel Model

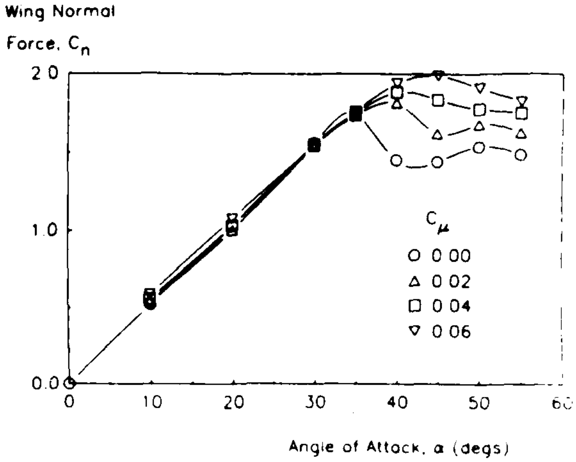

Figure 6: Effect of TLEB on Wing Normal Force.

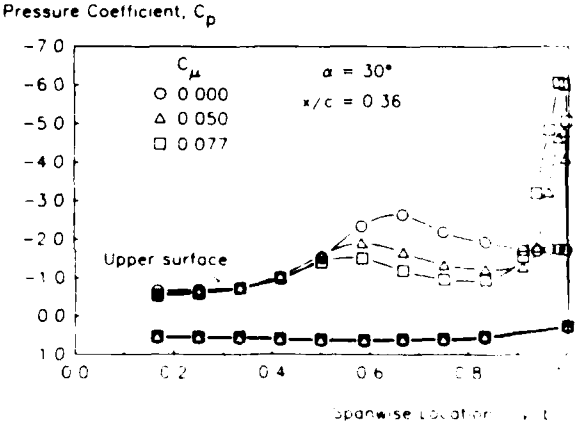

Figure 7: Spanwise Pressure Distributions for the Low Angle of Attack Case.

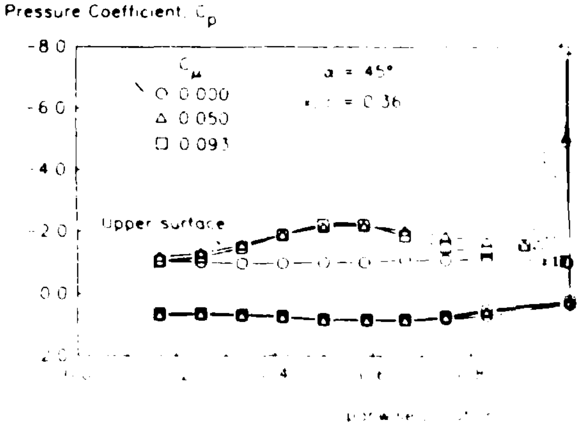

Figure 8: Spanwise Pressure Distributions for the High Angle of Attack Case.

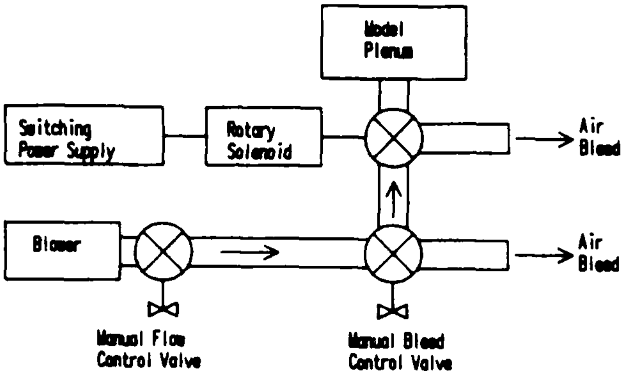

Figure 9: Unsteady Blowing Control System.

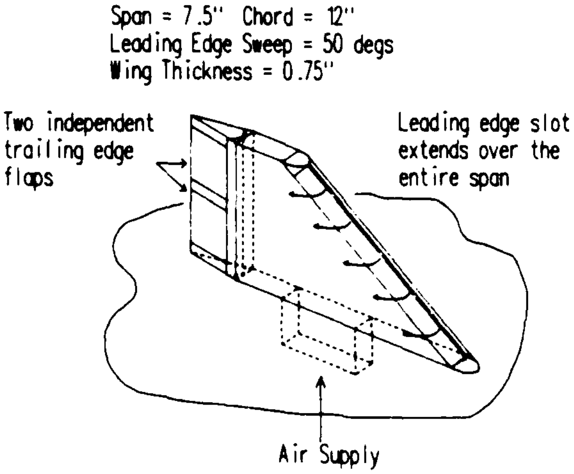

Figure 10: New Wind Tunnel Model.

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